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A TECHNIQUE FOR STRESS VISUALIZATION

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Synopsis : This paper is concerned with principles for a technique of stress visualization. This technique depends on the possibility of utilizing the yield phenomena of a carbon steel strip as revealed by a stress-strain diagram. To begin with, the physical meaning of the yield point elongation of the stress-strain diagram of carbon steel is investigated. The strains displayed on the horizontal axis are the striped patterns or stretcher strains that one can easily discern by the naked eye, while the stress displayed by the vertical axis is the specific yield stress as the stress is acting on the material. The striped patterns and the yield stress are two aspects of the identical phenomenon, and accordingly the two aspects maintain an exact correspondence. Any location on the test strip which is acted upon by yield stress is in a plastic state. Such a plastic state is visible to the naked eye in the form of striped patterns. Thus, the striped patterns renders the yield stress visually observable. In instances like this the special instruments for the detection of plastic states are not useful; but one need only polish the surface of the test strip to a fine smoothness in order to easily detect yield stress with the naked eye. One of the most useful stress visualization techniques is to utilize the striped pattern which always appears in concomitace with yield point elongation. As a concrete example of the visualization of yield stress, a plastic region is made visibly observable by applying both a tensile load and torque to a notch tip.

Key words : Notch, Experimental stress analysis, Torsion, Fracture mechanics, Tensile properties, Sensor, Stress measurement, Stretcher strains.

1. Introduction

The elucidation of the mechanical properties of elastic-plastic zones at notch tips is an important topic in mechanical enginering. It would be quite easy to obtain the requisite information about elastic-plastic zones if it were possible to make direct observation of them. On this account any simple method for making direct observation would be highly appreciated.

As a result of press work, striped patterns sometimes appear on the surface of the product. These striped patterns are called "Stretcher Strains" or "Luder's bands." Since the appearance of these striped patterns ruins the external appearance of the product, they are generally not a happily accepted phenomenon. Much research has already been done on these stretcher strains, however, almost all of this research has been carried out in the interest of preventing the appearance of stretcher strains. So far as the useful properties of stretcher strains are concerned, there has been only one instance of research on the use of stretcher strains for detecting dangerous sections[1].

The appearance of stretcher strains corresponds to yield stress[2]. This mechanical property of stretcher strains suggests that by means of stretcher strains it should be possible to directly observe with the naked eye when a portion of an elastic region will transform into a plastic region. By regarding stretcher strains as a sensor for the visualization of yield stress, the stretcher strains will stand as the directly observed results of inducing an elastic-plastic zone by applying tensile load together with torque to a notch tip.

2. The Principle of the Stress Visualization Technique

When a tensile load is applied to a rectangular tension test specimen, the striped patterns appearing on the surface of the test strip mutate in the way shown in Figure 1[3]. Figure 2 is the stress-strain diagram for these moments. When the load approaches the vicinity of the upper yield point, but-shaped striped patterns that are visible to the naked eye appear at the shoulder region and in the region parallel to the border. Following their initial appearance the striped patterns form a sloping line and cut across the left and right sides of the parallel portion ; subsequently they propagate facing the center and finally cover the entire area of the parallel portion. Figures 1 (a) through 1 (c) exhibit the striped patterns as they correspond to each of these various conditions. The notations of Figure 1 (a)-(c) correspond to the locations A through C on the stress-strain diagram of Figure 2. During the time that the striped patterns are propagating across the parallel portion, the stress has a fixed value of σ_y. At the moment that the striped patterns have completely covered the parallel portion, the stretcher strains throughout the test specimen mutate into orange peel patterns as illustrated in Figure 1 (d). When the load is removed, the striped patterns retain the pattern reached at that moment, but cease to spread. The stripéd patterns are visible only when the yield phenomenon is in operation.

The interval between ε_1 and ε_2 on the horizontal axis of the stress-strain dia-

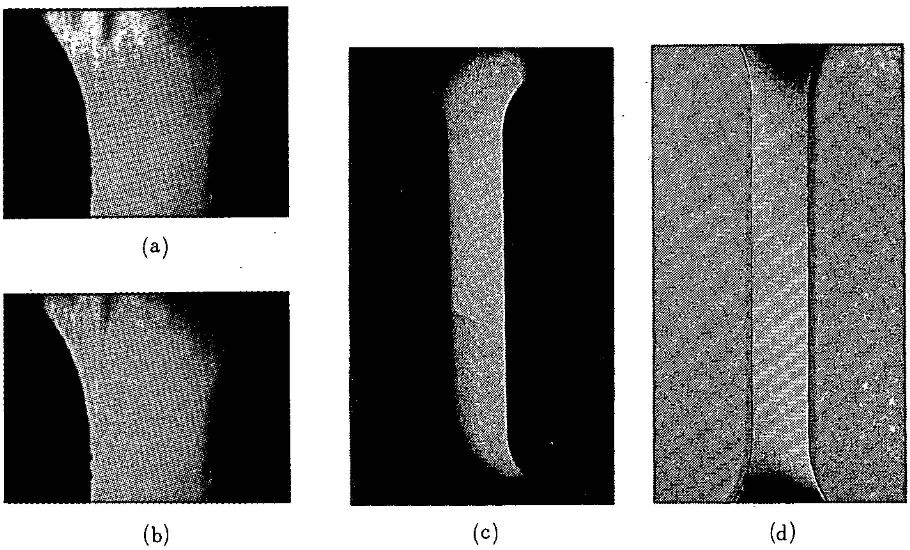


Fig.1 Surface state of test specimen

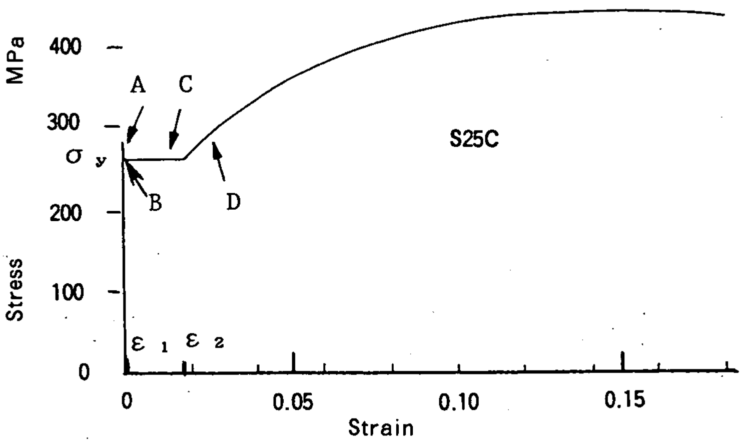
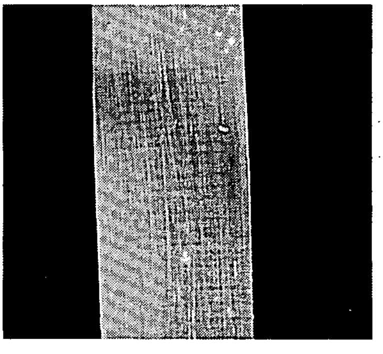


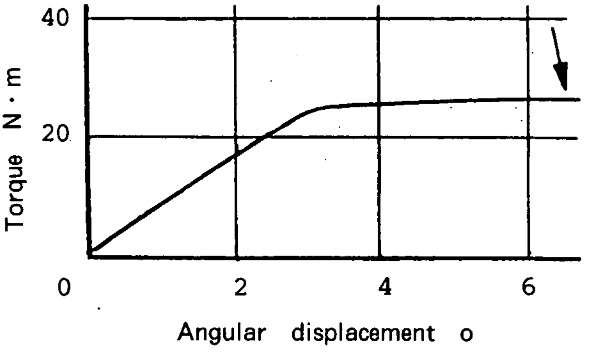
Fig.2 Stress-strain diagram

gram indicates strain in the yield area. Plastic transformation takes place in this interval. The striped patterns which appear on the surface of the parallel portion as a result of this plastic transformation are called stretcher strains. The value of the yield stress σ_y recorded on the vertical axis varies specifically with the material. One can ascertain from looking at the yield region in the stress-strain diagram that the yield stress σ_y corresponds to stress and the stretcher strains correspond to strain. The stretcher strains and the yield stress σ_y are two aspects of the same phenomenon, and the two values mutually correspond to each other. Whenever stretcher strains become visible, yield stress is operating and a plastic zone has come into being.

Figure 3 (1), (2) is a diagram for torque-angular displacement as well as for the striped patterns that appear on the surface when torque is applied to a test strip having exactly the same size and shape as the test strip in Figure 1. The striped patterns in Figure 3 (1) correspond to the location indicated by the arrow on the torque-angular displacement diagram in Figure 3 (2). A difference can be discerned between the striped patterns engendered from torque and the striped patterns which result from tensile load. The experimental results of Figure 3 indicate that these striped patterns correspond to yield stress.



(1)

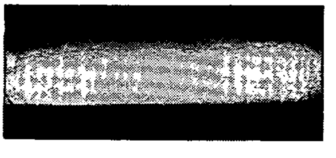


(2)

Fig.3 Striped patterns by torque and torque-angular displacement diagram

(1)

Patterns from compressive load



(2)

Patterns from bending moment

Fig.4 Yield stress pattern

Figure 4 (1) is a recording of the striped patterns which appear as a result of compressive load, while Figure 4 (2) [4] records the striped patterns which appear as a result of bending moment. From the recordings given in Figures 1, 3, and 4, it can be seen that stretcher strains break out when the stress acting on the test specimen approaches yield stress ; at this moment it is easy to discern from the stretcher strains whether the stress is tensile stress, shear stress, compressive stress, or some other kind of stress. Accordingly these Striped Patterns will henceforth be referred to as Yield Stress Patterns [5]. Yield stress patterns break out and propagate when as a result of yield stress a plastic zone emerges in the midst of an elastic region. As these yield stress patterns can be discerned by the naked eye they may be regarded as a kind of sensor. It is possible to discern what kind of stress is acting on the material by observing the form of the yield stress patterns that appear. In order to make use of yield stress patterns for investigating stress it is enough merely to polish the surface of a certain location to a fine smoothness. Yield stress patterns may be regarded as a simple sensor for the visualization of stress.

Besides carbon steel, stainless steel, Al-Mg alloy, and other types of material show yield stress patterns. It is possible to visually observe the appearance of the elastic-plastic state on test strips made of these materials as well.

3. The Condition of Plastic Zones Induced on a Notch Tip

3.1 The Test Specimen and the Method of Experiment

Figure 5 displays the shape and the dimensions of the test specimen. The total length of a JIS13B rectangular tension test specimen was measured to be 200 mm. A single notch was cut into the test specimen, as exhibited in Figure 5. The notch had a depth of 'a' and a notch radius of 0.05 mm. A common market variety S50C steel strip was used. Tabel 1 displays the chemical composition of the material. The test specimen was vacuum annealed after machine processing. In order to easily observe the appearance of yield stress patterns with the naked eye, the surface was finished to a fine smoothness with no. 2000 emery paper. The surface roughness of the finished test strip is recorded in Figure 6. The R_{max} value of the surface texture was determined to be 0.1 μm.

The tensile test was carried out using an Instron-type material testing machine. A video camera was used to make a continuous recording of the yield stress stripes

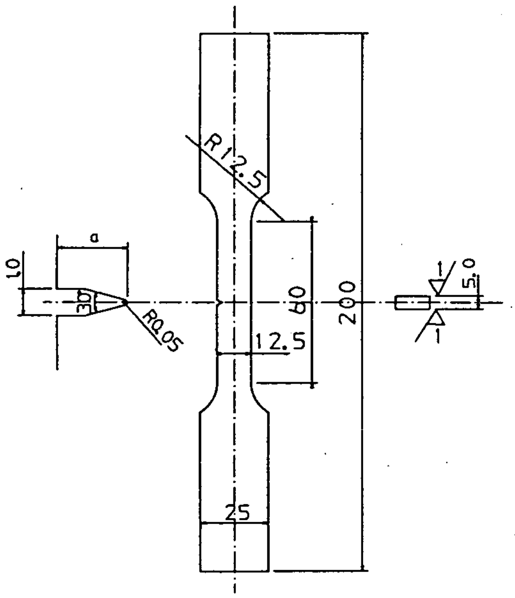


Fig.5 Test specimens

Table.1 Chemical composition of the specimens in percentage.

C	Si	Mn	P	S
0.12	0.21	0.55	0.013	0.019

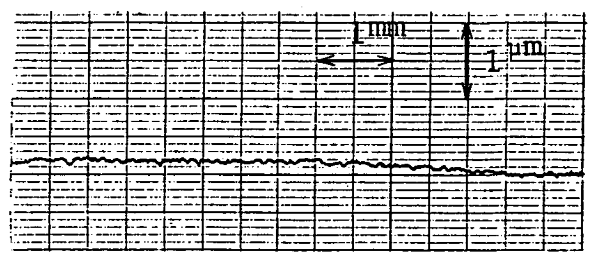


Fig.6 Profile of measurementof the surface roughness of specimen

appearing in the vicinity of the notch tip ; the data were recorded at a magnification of ten. For the sake of expediency in observing the phenomena, the speed of the test machine's cross-head was set at 0.1 mm per minute [6]. A strain gauge type of extensometer was used to measure the displacement of the test specimen. Using torsion testing equipment, observation was made of the condition of the notch tip when torque was aplied to the test specimen referred to in Figure 5.

3.2 The Yield Stress Patterns Engendered from a Tensile Load

The data of Figure 7 [7] indicate how, in conjunction with an increase in tensile load, yield stress patterns appeared on the surface in the vicinity of a notch tip. The yield stress patterns mutated in the sequence from (1) to (6). In Figure 7 (1) the yield stress patterns first appear at the notch tip in tiny bud-shaped formations.

Immediately after first appearing the yield stress patterns swell in a circular shape in proportion to the increase in tensile load until they appear as seen in Figure 7 (3)-(6). At this stage, instead of propagating at an even speed, they were ascertained to progress by tiny repetitions.

One can infer from the yield stress patterns of Figure 7 (1)-(6) that the yield stress associated with yield point elongation has transformed part of the elastic region into a plastic region. Thus it is apparent that a plastic region has been brought about in the vicinity of the notch tip by application of a tensile load. As the tensile load in the vicinity of the notch tip increased a plastic region appeared in the order given by Figure 7 (1)-(6). It was possible to make continuous and unproblematic observation of the elastic-plastic states with the naked eye by observing the yield stress patterns on the carbon steel strip. It was thus possible to make visual observation of elastic-plastic states.

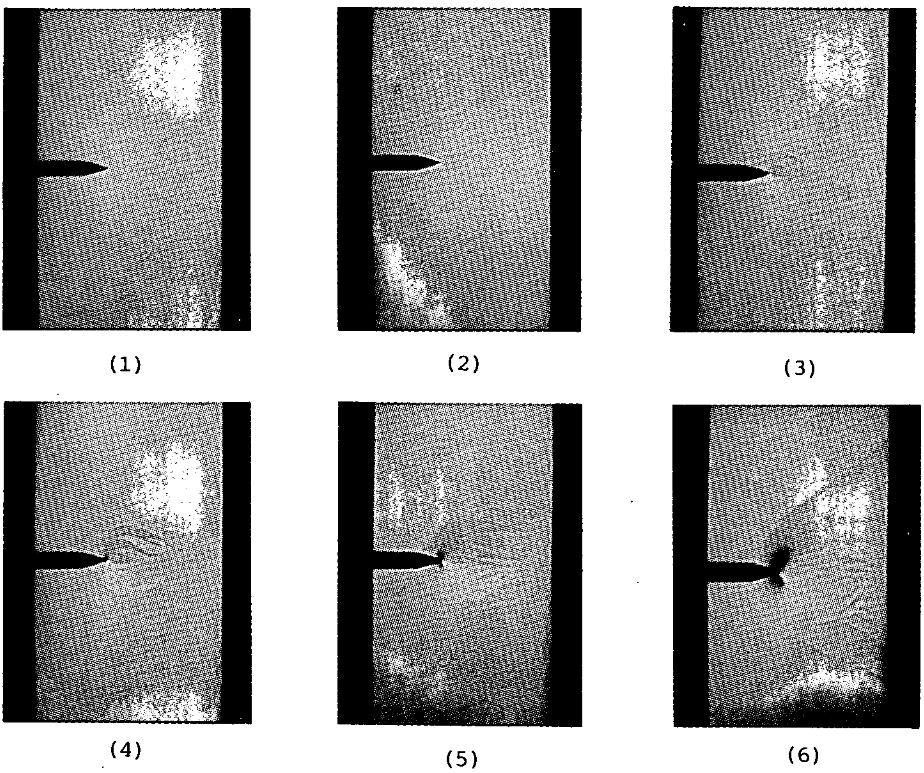


Fig.7 Yield stress patterns at the notch tip by tensile load

3.3 The Load-Displacement Diagram

Figure 8 is the load and displacement diagram for the moment when the data of Figure 7 were recorded. In Figure 8 the locations (1)-(6) correspond to the moments (1)-(6) in Figure 7 when the plastic zones appeared. Point (1) of Figure 8 is the value for the tensile load and the displacement at the moment when the plastic zones appear. This point in the diagram appears within the region where the tensile load is in direct proportion to the displacement. Point (1) in Figure 8 corresponds to a tiny stretch within the elastic zone of Figure 7 (1) that has transformed into a plastic zone. It is very difficult to ascertain the tensile loads corresponding to point (1) in Figure 8 by etching or some other experimental method. However, by visual observation on the basis of yield stress patterns it is very easy to ascertain the tensile load at which plastic zones will break out from place to place within the elastic zone. By using Figure 7 in conjunction with Figure 8 it is possible to ascertain the stress corresponding to the shape and dimensions of a plastic zone appearing on a

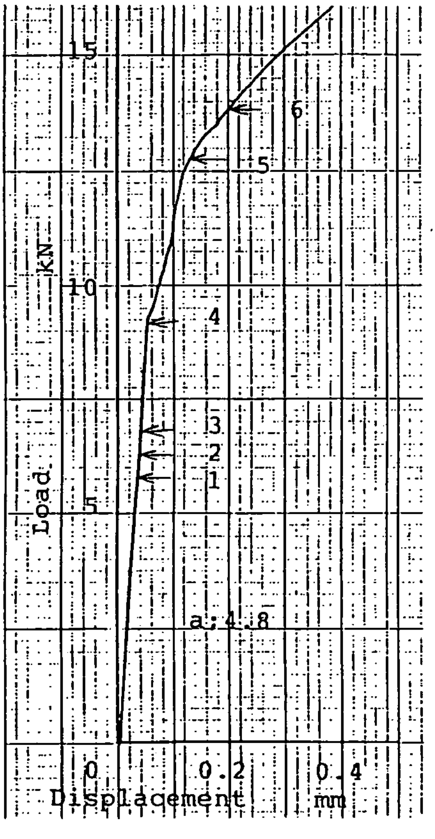


Fig.8 Load-displacement diagram

test strip. Thus the relation of the shape and dimensions of a plastic zone to load is a crucially important datum about the stress at a notch tip.

3.4 The Width of the Plastic Zone

Figure 9 was obtained by applying a tensile load to a notch tip and collating the experimentally measured widths of the plastic zones that appeared there with the tensile load P. The depth of the notch was 2.1 mm. It was ascertained that as the tensile load increases, the width of the plastic zone increases. The following regression equation was obtained by making a regression analysis of the experimentally measered values:

$$r_p = 0.664P - 7.71 \tag{1}$$

In this equation P is measured in units of kN and r_P is measured in millimeters. The dotted vertical line recorded in Figure 9 represents the regression equation, while the curved line above and below it represents a 95% confidence limit for that equation.

It was possible to ascertain the width of the plastic zone in relation to load by means of a finite element analysis. The results are exhibited by the phantom line in Figure 9. If the value for the width of the plastic zone is small one may assume that the experimentally measured value is the same as the value obtained by finite element analysis.

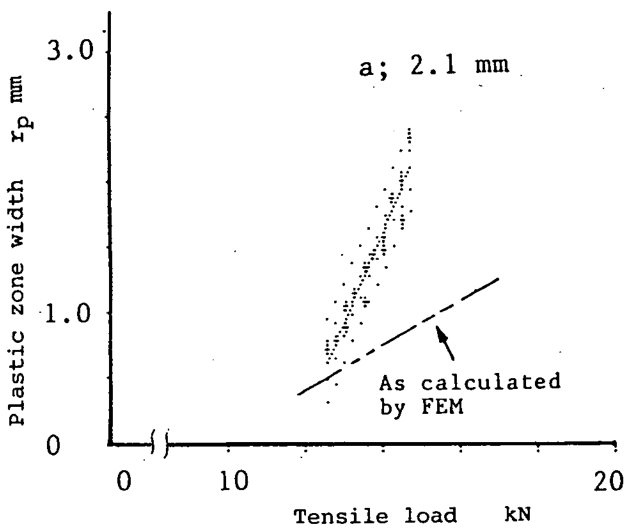


Fig.9 Plastic zone width in relation to tensile load

3.5 The Shape of the Plastic Zone

The shape of the plastic zone of Figure 7 (4), as ascertained by visual observation of the yield stress patterns, resembles the plastic zone as displayed by etching in the scholarly literature [8]. Figure 10 results from combining the locus of the von Mises criterion with the value K_1 for the shapes of the plastic zones in Figure 7 (3). The experimentally ascertained plastic zones and the locations of the yield criterion connected by the curved line are located between (b) the plane stress state and (a) the plane strain state.

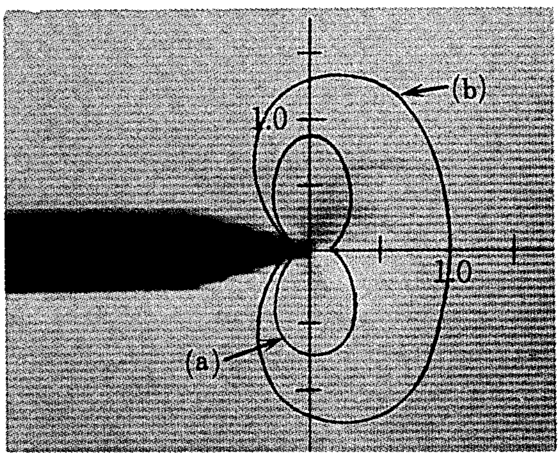


Fig.10 Plastic zone shape in relation to the loci of the von Mises yield criterion[9]

3.6 The Yield Stress Patterns Engendered from Torque

Figure 11 is an example of the continuous data that are obtained when yield stress patterns are brought about by the application of torque to a notch tip. When the yield stress patterns first break out they have the shape of flame tips and grow in the direction of the notch tip. When the torque reaches a relatively greater value, striped patterns that appear like the patterns in Figure 11 (5) emerge and propagate toward the vertical axis of the test specimen. Figure 12 is the torque-angular displacement diagram for the moment when the data of Figure 11 were recorded. The numbers in Figure 12 correspond to the numbers in Figure 11. The experimental results given in Figure 12 lend additional support to the conclusion that the striped patterns of Figure 11 are engendered from yield stress.

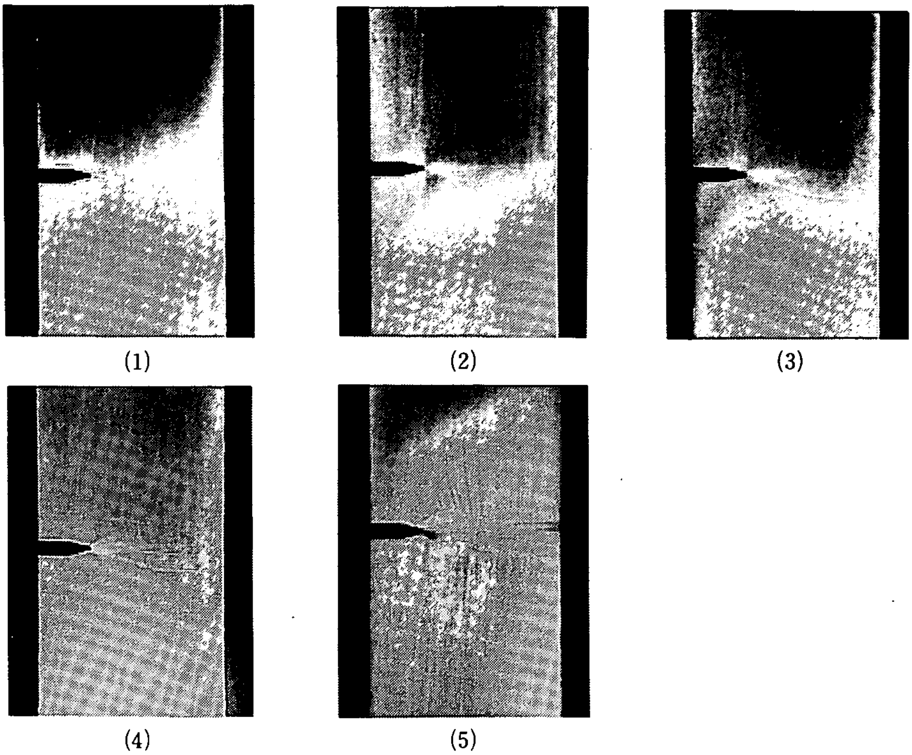


Fig.11 Propagation of the yield stress patterns in the notch-tip region when subjected to torque

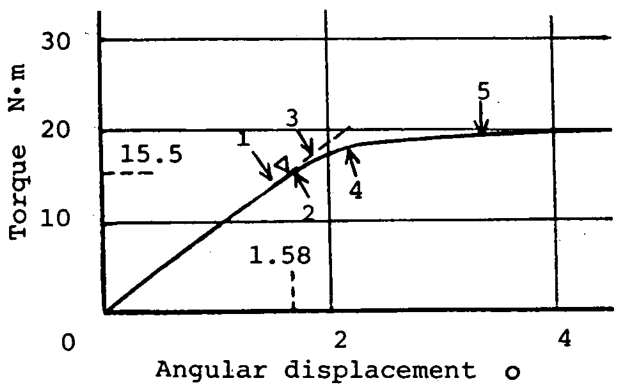


Fig.12 Propagation of the yield stress patterns as shown by the torque-angular displacement diagram

4. Conclusions

Yield stress patterns can be used as a visual yield stress sensor. In order to use yield stress patterns as a sensor one need only polish the locations to be investigated to a fine smoothness. Yield stress patterns provide an extremely easy means to detect stress. It has been confirmed that yield stress patterns can be used to analyze stress by means of direct observation of elastic-plastic states.

5. References

1) Timoshenko, S., Strength of Materials Part II, 3rd Ed., (1958), Van Nostrand, New York, 330.

2) ASM, Metals Handbook 10th Ed., Vol.1, (1990), 217.

3) Taniuchi, K., Stress Visualization Techniques for the Experimental Analysis of Elastic-Plastic Properties of Shoulder Fillets, Experimental Mechanics, (1992), 59, Elsevier Science Publishers.

4) Taniuchi, K., Stretcher-Strain Markings on Low-Carbon Steel Bars Caused by Bending, Research Reoport of the Faculty of Engineering, Meiji University, No.50, (1986-3), 15.

5) Taniuchi, K., Simple Stress Sensor : Utilizing of Stretcher Strains, ASTM STP 1025, (1989), 217.

6) Taniuchi, K., Satoh, T., Results Observed on the Texture of Stretcher Strains of Low-Carbon Steel Plates, Research Report of the Faculty of Engineering, Meiji University, No.49, (1985-10), 15.

7) Taniuchi, K., The Visualization of Elastic-Plastic Zones, Proceedings of the VII International Congress on Experimental Mechanics, (1992), 1005.

8) Gdoutos, E.E., Fracture Mechanics Criteria & Applications, (1990), 93, Kluwer Academic Pub.

9) Taniuchi, K., A Study of Irwin's Plastic Zone Adjustment, Memoins of the Institute of Seience and Technolgy, Meiji University, vol.32 No.1, (1993), 1.